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REPORT OF RESEARCH WORK IN WHEAT STORAGE
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The storage of wheat on the farm has in the past few years received much attention from both farmers and Government agencies. Many questions and problems have arisen as to the best types of storage structures for the farm, the relative suitability of the various materials of construction, the grades and moisture content of wheat that can be safely stored for long periods, effectiveness of underground storages, the use of absorbents for drying wheat in storage, the suitability of various bin designs for fumigation, the possibilities of developing a portable wheat drying machine that can economically remove enough moisture from damp wheat to make storage safe, and bin ventilating systems for damp wheat. In order to find an answer to these questions, a research program, supported by Bankhead-Jones funds, was instituted in 1936 by the Department of Agriculture, represented by the Bureaus of Agricultural Engineering, Plant Industry, and Agricultural Economics, and the Agricultural Experiment Stations of North Dakota, Kansas, Illinois, Maryland, Ohio, Michigan, and Minnesota. In 1936 and 1937 the State Mill and Elevator of North Dakota also cooperated by lending large quantities of wheat for use in the experiments in that State. Field stations and experimental bins were set up at Fargo, North Dakota; Hays, Kansas; Urbana, Illinois; and College Park, Maryland; each in cooperation with the respective agricultural experimental station. Thus, all the wheat-growing regions except the Western Coast were included in the

investigations. The experimental bins ranged in size from 20-bushel to 1000-bushel capacity, about 10 of the small and 8 to 12 of the larger bins being erected at each station. These bins varied in materials of construction, amount of insulation, size, and type of ventilating systems, if any.

The different bins and ventilating systems were compared by noting the temperature changes of the grain in different parts of the bin, the rates at which moisture was removed from the stored wheat, the commercial grade of the wheat when placed into storage and during the storage period, and the changes in the condition of the wheat as indicated by its fat acidity 1/ and percent germination. Temperatures of the stored wheat were obtained by thermocouples placed in representative locations and read by means of a potentiometer. Average samples were taken from the bins with standard grain triers and analyzed by the official grain inspectors of the Agricultural Marketing Service to determine moisture content, grade, fat acidity, and milling and baking qualities. The Bureau of Plant Industry determined percent germination of the same samples. In order to learn the condition of the wheat in different parts of the bins, additional samples were taken from selected locations and tested for moisture content, fat acidity, and germination.

Those bins at each station used for determining the relative merits of the different materials of construction--wood, metal, and concrete--were all filled from the same lots of wheat through a large divider, so that the wheat in all bins would be as nearly identical as possible. For determining the maximum moisture content and temperature

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1/ The fat acidity determination is a chemical test based upon the amount of free fatty acids in the wheat. Fat acidity is determined by the number of milligrams of potassium hydroxide required to neutralize the free fatty acids in 100 grams of wheat.

for safe storage over various lengths of time, identical bins were filled with wheat of moisture contents slightly above, equal to, and slightly below that specified by the official grain standards for the straight numerical grades of the various classes of wheat. Field studies of ventilation were made at all of the stations, in bins of several capacities, up to 1000 bushels. These were filled with moderately damp wheat, then closely observed for as long as necessary to determine the value of the equipment and methods used.

Storing of damp wheat in ventilated bins may not always prove dependable and economical; hence, in 1937 the development of low cost portable dryers employing artificial heat was started. Two methods, differing in the manner of using heat and air, are being tested. Good results are being obtained at the University of Maryland with a dryer in which the grain is heated by being passed through an extended surface heating coil while a stream of cool air flows over it in the opposite direction to remove the moisture. The moisture content of 17% wheat can be lowered to 13% by this machine at a rate of 50 bushels per hour. By reducing the rate of feed, the amount of moisture removed can be further increased. Coal is used for fuel and water as the heat carrier. Another type of machine, being developed at Arlington Experimental Farm, Rosslyn, Virginia, heats the grain by direct contact with the inside of a drum revolving in a heated oven. The wet wheat, heated to a temperature of about 140° F., passes by gravity down between two screens spaced about six inches apart, where it receives a blast of cool air. The wheat is in the air flow for a period of 8 to 10 minutes, in which time it is both cooled to air temperature and dried. The experimental model built in 1939, mounted on a truck, will dry 16% wheat to 14% at the rate

of 100 bushels per hour. Oil is used for fuel. This type of machine was described in greater detail in an article, "Methods for Drying Grain on the Farm," published in Agricultural Engineering for April, 1939.

To check experimental data obtained at the field stations, several surveys of storage conditions on farms have been made. The storage of wheat under seal by the A. A. A. has provided additional opportunity for us to observe wheat of which the initial condition was known.

Laboratory tests have been conducted along several lines. The Bureau of Plant Industry, in its Washington laboratories, has experiments under way to determine the part played by fungi in the spoilage of wheat and the effectiveness of certain fungicides in inhibiting such spoilage. The spoilage known in the trade as "sick wheat" is also being studied.

As stated before, samples are taken from the wheat under observation for moisture, grade, milling and baking, germination, and fat acidity tests. These samples are, of course, used to determine in the laboratory the extent of deterioration. In this connection it was found that the external evidences of wheat deterioration usually are not apparent until the condition of the grain has been lowered enough to affect its commercial grade. However, percent germination and fat acidity of sound wheat were found to be valuable indices of incipient deterioration that is not apparent from grade examination. Changes in both germination and fat acidity are found to be accelerated under high moisture and temperature conditions, and these changes are measurable before the development of abnormal odors or kernel damage. With wheat of low moisture content and low temperature conditions there is little loss in germination or increase in fat acidity.

Laboratory experiments were also conducted in Washington and in the field stations to determine basic data for the design of ventilating

systems. These included tests and calculations to determine air pressures available from the wind, rates of air flow through wheat under low static pressure, effect of chaff, bin-wall surface area and wheat density on rate of air flow, and rates of moisture removal from stored wheat under various conditions of air flow and grain depth. These data, as well as the results of the tests of ventilated bins, will soon be published in a circular, "Methods of Ventilating Wheat in Farm Storages." Since this circular went to press, additional information on the effect of temperature on the moisture equilibrium of wheat has been obtained in the Washington laboratories.

Recently an experiment was set up to determine the effect, if any, of storage in creosote-treated bins on the odor, official grade, germination, and milling and baking qualities of the stored wheat.

Several problems which are of immediate interest at this time in connection with farm storage structures are (1) strength requirements, (2) weather tightness, (3) insect control, and (4) bin ventilation.

Strength Requirements

No recent investigations have been made of the various pressures produced in a structure by stored wheat. However, several mathematical treatments, as well as a description of numerous experiments to determine the law of grain pressures are given in detail in "The Design of Walls, Bins, and Grain Elevators," by Milo S. Ketchum. The calculated solutions, obtained by means of either Janssen's or Airy's formulas, agree closely with experimental data. An article by J. D. Long, "The Design of Grain Storage Structures," published in the July, 1931, issue of "Agricultural Engineering" summarized the existing knowledge of

structural design of grain bins and cited several types of failures and their causes.

Because all formulas make use of one or more constants, the values of which vary with the kind and condition of grain to be stored and the material of bin construction, much judgment in selecting the proper values must be used in design work of this type, and on large structures an experienced engineer should be consulted. It should be remembered that even in small bins the pressures are quite large. For instance, in a 1000-bushel rectangular wood bin, 12'-0" x 14'-0" x 8'-0" high, filled with wheat weighing 50 pounds per cubic foot, the lateral pressure at the bottom of the side wall will be about 180 pounds per square foot, the load carried by the side walls 340 pounds per lineal foot and the pressure on the bin bottom about 290 pounds per square foot. A round metal bin, 14'-0" in diameter and 8'-0" high, capacity about 1000 bushels, and filled with the same kind of grain, will have a lateral pressure at the bottom of about 190 pounds per square foot, a load carried by the side walls of about 300 pounds per lineal foot, and a pressure on the bin bottom of about 310 pounds per square foot. In a larger metal bin, 2036-bushel capacity and 18'-0" in diameter by 10 feet high, the lateral pressure at the bottom will be about 240 pounds per square foot, the load on the bin walls per lineal foot about 470 pounds and the vertical pressure approximately 400 pounds per square foot. In making these calculations Janssen's formula--$L = \frac{wR}{u'}\left(1 - e^{-\frac{ku'h}{R}}\right)$--was used, with the following nomenclature:

L = lateral pressure of wheat in pounds per square foot

w = weight of grain in pounds per cubic foot

R = hydraulic radius of bin

u' = coefficient of friction of wheat on bin wall

k = ratio of lateral to vertical pressures

h = depth of grain in feet

A value of 0.6 was used for k, 0.441 for the coefficient of friction of wheat on wood, and 0.365 for coefficient of friction of wheat on metal. The pressures as calculated above are approximately the same as would be obtained with Airy's formula using an angle of repose for wheat of 18°.

Ordinarily, the wall material of one to two thousand bushel round metal bins is strong enough to take the "hoop" tension. However, structural failures may occur in the vertical seams between wall sheets or at the junction of the wall sheets with the door frames because of too small or an insufficient number of bolts, or because the designer failed to realize that a bolt put in place in the field may not make as efficient a joint as can be obtained in the shop with the same fastening. The entire bursting pressures below the top of the bin door are transmitted to the door frame, and this feature must be of heavy enough construction to prevent noticeable deflection. Some prefabricated bins now on the market are weak in this respect.

The design of wooden bins for strength is very well covered in Farmers' Bulletin 1636, "Farm Bulk Storage for Small Grains," and in "Wheat Storage in the Ever-Normal Granary." These publications include tables giving the safe size and spacing of studs and joists for farm grain bins of various depths, and the safe loads for various sizes and spans of joists.

Weather Tightness

An otherwise well-constructed bin, filled at harvest with good dry wheat, may not safely store the grain because of failure to keep out rain and snow. Rain, driven by wind, will enter a bin through small holes in the roof, cracks in the walls and around ventilators, or at the floor line in some types of construction. Rain leaking in through a hole in the roof will usually run straight down to the floor, resulting in a core of spoiled wheat under the roof opening, and a spoiled condition of the grain on the floor which may be attributed to some other cause. It has been found in the northern states that it is sometimes more difficult to make a bin tight against snow than against rain. Experimental bins at Fargo that were well-built and excluded rain, allowed several inches of snow to blow in on top of the grain in one blizzard. If the snow is shoveled out before it melts, it, of course, does little harm, but it must be remembered that it may melt under the roof before it does on the ground. Our engineer at Fargo observed snow melting on a bright day in a metal bin at an outside temperature of -2° F. The water from such slow melting causes an increase in moisture content of the wheat in the upper layers. A certain amount of it may run down the wall to the floor. Another source of trouble from snow may occur in the spring when drifts against the south side of the bin begin to melt sooner than the snow farther away, the trapped water running into the joint between the side walls and bin floor. The remedy for the above failures are obvious--make all joints in bin walls and roof weather tight, using caulking compound if necessary, close ventilators in winter months by plugging with burlap sacks, and build bin on a foundation high enough to give proper drainage from both rain and melting snow.

Insect Control

The Bureau of Entomology and Plant Quarantine states that millions of dollars are lost yearly by farmers because of damage to stored grain by weevils and the Angoumois grain moth. This past year the engineer in charge of the storage investigations at Hays, Kansas, made a survey of farm wheat bins in the eastern and central sections of that State. In July, shortly after harvest, samples were obtained from 49 bins, the wheat moisture contents ranging from 10.4% to 17.3%. No insects were found at that time. In the latter part of September, about two months later, 22 of the bins around Wichita were revisited and sampled, and 18 were found to be infested with bran bugs and flour worms, eleven severely enough to be graded "weevily". Only one of these bins was under seal for a loan, and so should not be confused with the cases cited in the preceding paper.

Insect loss after the grain is in storage can be prevented by fumigation. The usual method is to use a heavier-than-air gas that will penetrate down through the grain mass. It is necessary that the bin walls and floor be tight, the effectiveness of any fumigant being in inverse proportion to the number of cracks and openings.

The Bureau of Entomology and Plant Quarantine, in Farmers' Bulletins 1483 and 1811, give complete directions for controlling insects in stored grain by fumigating with specific fumigants and also gives accounts of the life cycles and habits of the more important insect pests found in grain.

Bin Ventilation

Damage to damp wheat in storage is usually caused by the activity of microorganisms and by excessive respiration of the wheat kernel. Heat is evolved by the microorganisms and by kernel respiration at a rate depending to a large extent on the wheat moisture content and temperature. Where the heat generated is not removed promptly, it will raise the wheat temperature and increase the rate of respiration, this "self accelerating" process continuing until the grain is unfit for human consumption. Insect infestation also may, in addition to the damage caused by the actual feeding upon the kernel, produce enough heat and moisture to start this "self accelerating" process. Therefore, in designing ventilated structures for the safe storage of damp wheat, in addition to insect control two problems must be solved--the dissipation of heat and the removal of moisture from the wheat. Both must be accomplished before material damage has occurred.

The excess heat evolved may be transferred from the wheat mass to the bin wall by conduction or radiation, and then to the surrounding air, or may be removed by convection currents of air. Tests made in connection with this investigation by the National Bureau of Standards indicate that for wheat with a moisture content between 12.5 and 14 percent the thermal conductivity varied from .89 to .98 Btu per hour per square foot per inch thickness. This means that wheat as an insulator is about as effective as sawdust, and will resist the transfer of heat

from the wheat mass to the bin wall. Many temperature readings taken by means of thermocouples in the wheat mass have shown that, where conduction and radiation alone are depended upon, the removal of heat from a large bin of damp wheat is not fast enough to prevent the building up of temperatures dangerous for safe storage. The amount of heat transfer by conduction may be increased by shortening the distance of heat travel, and this method is used in some types of bin ventilating systems. However, for rapid removal of heat from large masses, air flow through the grain is necessary.

Air flow is also necessary for the drying of wheat, the rate of moisture removal depending upon the amount and condition of air, wheat temperature and moisture content, and length of air travel through the wheat. In bins with tight walls and bottoms and with no ventilating flues or other equipment, we have found little change in wheat moisture content, except in the top six inches or one foot, even though a ventilator is fitted into the roof to provide air circulation above the grain.

The problem of bin ventilating system design is complicated by the fact that air movement is necessary for ventilation but a hindrance to insect control. Any openings in the sides or bottom of a ventilated bin must be so arranged that they can be easily sealed when necessary to fumigate.

The higher average wind velocities and lower relative humidities make natural or wind-operated ventilating systems more effective in the area west of the Mississippi River than in the more humid sections farther east. Two systems, both utilizing the pressure developed by the wind, were tested at Fargo, North Dakota and Hays, Kansas, and found to store wheat safely with an initial moisture content of from one to two percent higher than could safely be stored in unventilated bins in

the same areas and appear to be practical for use on the farm in those areas. These systems also allow fairly easy sealing of the bins for fumigation.

Both designs have a large cowl, throat diameter about 12 inches, above the bin which is kept headed into the wind by a vane. Wind pressure forces air from this cowl into a round pressure chamber, covered with screen or perforated metal, in the center of the wheat mass. In a 1000-bushel round bin 14 feet in diameter and 8 feet high, the air chamber or drum used is about 1 foot thick and 7 feet in diameter. The bin floor must be of screen or perforated metal, so that the drying and cooling air can leave at both the top and bottom of the bin after traveling through 3 1/2 feet of wheat. The advantage of introducing the air at the bin center and forcing it out through the top and bottom surfaces of the wheat is twofold: (1) The cool dry air will first dry out the center of the mass where trouble from heating and molding is first likely to develop and (2) any increase of wheat moisture content due to deposition of moisture on cool wheat will occur near the bottom or top of the bin where it may more easily be picked up by the outside air. By banking earth around the bottom of the bin and closing the one duct leading from the cowl to the drum, the wheat stored in a bin of this type can be effectively fumigated.

The second design is more suitable for installing in a wooden bin. Air from the pressure cowl is led to two layers of flues, one layer at the floor level and the other two-thirds of the distance up from the floor. These flues, of 1" x 4" boards on edge about 4 inches apart and covered with fly screen, should be spaced horizontally about 2 feet on centers. The ends of the flues not connected to the cowl are closed. A third layer of flues, half way between the two inlet layers, serves

as an exit for part of the ventilating air, the remainder passing out through the upper surface of the wheat. Both ends of the outlet flues are open to the air. By pasting paper over or otherwise closing the ends of the outlet flues, and closing the large duct leading to the pressure cowl, this type of bin can also be effectively fumigated.

Either of the above described ventilating systems can be easily adapted to power ventilation by replacing the pressure cowl with a blower. If a blower of adequate capacity (1 to 1 1/2 cubic feet of air per minute per bushel of wheat) and a few hours of reasonably dry weather are available each day, as is usually the case in the western wheat areas, such systems should dry wheat of 18 percent moisture content without damage.

At Hays, Kansas, bins with perforated floors but without means for forcing air through the wheat were effective for equalizing moisture between wet and dry layers; however, they removed very little moisture. They probably do not raise the safe average initial moisture content by more than 0.5 percent, and are not recommended for the Soft Red Winter wheat area. The efficiency of such a ventilating system can be considerably increased by adding a suction cowl on the roof of the bin and tightly closing all openings above the wheat. In western Kansas, the cowl will probably raise the safe storage moisture content 1 to 1 1/2 percent higher than for wheat stored in non-ventilated bins, but its effectiveness in regions of high humidity is limited.